



AIAA-95-3368

Descent Advisor Preliminary Field Test

S. Green

**NASA Ames Research Center
Moffett Field, CA**

**R. Vivona and B. Sanford
Sterling Software Inc.
Moffett Field, CA**

**AIAA Guidance, Navigation, and Control
Conference**

August 7-10, 1995 / Baltimore, MD

DESCENT ADVISOR PRELIMINARY FIELD TEST

Steven M. Green*
NASA Ames Research Center
Moffett Field, California

Robert A. Vivona† and Beverly Sanford‡
Sterling Software Inc.
Moffett Field, California

Abstract

A field test of the Descent Advisor (DA) automation tool was conducted at the Denver Air Route Traffic Control Center in September 1994. DA is being developed to assist Center controllers in the efficient management and control of arrival traffic. DA generates advisories, based on trajectory predictions, to achieve accurate meter-fix arrival times in a fuel efficient manner while assisting the controller with the prediction and resolution of potential conflicts. The test objectives were (1) to evaluate the accuracy of DA trajectory predictions for conventional- and flight-management-system-equipped jet transports, (2) to identify significant sources of trajectory prediction error, and (3) to investigate procedural and training issues (both air and ground) associated with DA operations. Various commercial aircraft (97 flights total) and a Boeing 737-100 research aircraft participated in the test. Preliminary results from the primary test set of 24 commercial flights indicate a mean DA arrival time prediction error of 2.4 sec late with a standard deviation of 13.1 sec. This paper describes the field test and presents preliminary results for the commercial flights.

Introduction

Continued growth in air traffic has outpaced the expansion of our nation's air traffic capacity, resulting in increased workload and delays. The Center-TRACON Automation System (CTAS) is being developed to maximize the efficient use of terminal airspace and runway capacity.¹ CTAS will assist air

traffic controllers in the efficient management and control of traffic within the extended terminal area (to 100-200 n.mi. before top of descent (TOD)). The system is being developed to work in both voice and data link communication environments and to handle both conventional- and flight management system (FMS)-equipped aircraft types.²⁻⁴

CTAS is composed of three major elements: the Traffic Management Advisor (TMA), the Descent Advisor (DA), and the Final Approach Spacing Tool (FAST). DA predicts the trajectories of aircraft operating in Air Route Traffic Control Center (Center) airspace and provides estimated-time-of-arrival (ETA) data to TMA to determine traffic level. TMA scheduling algorithms map the traffic level against the airspace system capacity, based on runway configuration and separation criteria. TMA generates a traffic management plan that maximizes throughput and distributes necessary delays in an efficient manner. The TMA plan sets the arrival sequence and determines target scheduled times of arrival (STA) at the runways and meter fixes. DA assists the Center controller in accurately meeting meter-fix STAs in a fuel-efficient manner while also assisting in the prediction and resolution of potential conflicts.^{4,5} As aircraft enter the terminal-radar-approach-control (TRACON) airspace, FAST updates the analysis of traffic level and capacity and assists the TRACON controller in sequencing and spacing aircraft approaching the runway. By integrating traffic management across airspace boundaries and developing advisories for fuel efficient, conflict-free trajectories, CTAS has the potential to significantly reduce delays and workload as well as improve fuel efficiency.

A significant challenge in air traffic control (ATC) automation design is the development of algorithms that determine effective clearance advisories. To ensure effectiveness, these algorithms require a minimum level of trajectory prediction accuracy. Trajectory prediction

* Research Scientist, Member AIAA.

† Aerospace Engineer, Member AIAA.

‡ Human Factors Engineer

Copyright © 1995 by the American Institute of Aeronautics and Astronautics, Inc. No copyright is asserted in the United States under Title 17, U.S. Code. The U.S. Government has a royalty-free license to exercise all rights under the copyright claimed herein for government purposes. All other rights are reserved by the copyright owner.

errors tend to grow with the predictive time horizon[§] and are greatest when aircraft are to perform large transitions in altitude and velocity. The arrival time error at the meter fix, which represents the cumulative effect of errors over the descent trajectory, is a key measure of DA performance. The goal in developing DA is to routinely achieve a trajectory prediction accuracy of 20 sec, over a time horizon of 10–20 min, when an aircraft transitions from cruise to the arrival phase of flight. This level of accuracy is expected to increase the effectiveness of traffic management automation,[¶] increase the effectiveness and fuel efficiency of trajectory planning, and provide a foundation for automation of conflict prediction/resolution.

This paper describes a field test of DA trajectory-prediction accuracy, involving commercial flights for the first time, that was conducted at the Denver Center in September 1994. After a brief summary of results from previous simulation and field test studies, the September 1994 test is described in detail. Results and insights gained from a preliminary analysis are summarized.

Previous Evaluations

Previous evaluations of DA trajectory prediction accuracy, including piloted simulation and flight testing, have yielded positive results. These evaluations were based on the issuance of a single DA-based descent clearance with no corrective updates.

Real-time simulation studies, employing a phase-2 Boeing 727-200 simulator operated by line pilots, evaluated DA accuracy under a variety of conditions. For straight descents, the results indicated a mean arrival time error at the meter fix of 6.1 sec late, with a standard deviation of 13 sec.⁶ For curved-path descents involving a single turn of 60° during descent, the results indicated a mean arrival time error at the meter fix of 13.4 sec late, with a standard deviation of 15.6 sec.⁷ Conventional navigation techniques resulted in turn overshoots which led to a greater distance being flown than predicted. The study suggested that the increased

time error, due to turn overshoot, may be reduced by empirically modeling the turn dynamics of conventional aircraft.

A flight test employing the NASA Transport Systems Research Vehicle (TSRV) Boeing 737-100 aircraft and flight-test crew was conducted at Denver in 1992. The objective was to evaluate DA accuracy for straight-path descents and study the impact of errors in atmospheric and performance modeling under field conditions. The test also compared "idle-thrust" vs. "constrained" descent procedures to determine the extent that pilot corrections to the altitude profile would reduce the impact of modeling errors on trajectory prediction accuracy. The flight test was conducted over a 10-day period and included 26 descent runs. Unpublished results showed a mean arrival time error of 7 sec late with a 12-sec standard deviation. Performance modeling errors, which averaged 5% of net thrust (thrust-drag) over the descent, accounted for less than 3 sec of the mean error. The majority of the mean error, and nearly all of the variation, was due to wind modeling errors. When pilots used constrained procedures, substantial reductions in altitude and time error along the path were achieved, particularly with the assistance of cockpit automation for visualizing the altitude profile.

Test Description

Objective

The primary goal of the September 1994 test was to evaluate DA trajectory prediction accuracy for curved-path descents under field conditions. The test involved both United Airlines (UAL) commercial flights and the NASA TSRV. The objectives for the commercial flights were to evaluate DA accuracy over a representative set of jet transport types, study procedural issues associated with DA-based clearances, and compare differences in procedures and DA accuracy for conventional and FMS-equipped aircraft types. The objectives of the NASA TSRV flights were to evaluate DA accuracy for various levels of cockpit automation as well as to identify and measure the major sources of DA trajectory prediction error. Possible error sources include the modeling of atmospheric characteristics (wind and temperature aloft), aircraft performance and pilot procedures, and radar tracking.

[§] These errors may be reduced by FMS control over path, altitude, speed, and/or time.

[¶] Recent analysis indicates that significant reductions in operating cost (reduced delays and fuel consumption) can be achieved if meter fix arrival time errors are reduced from 2 min (an optimistic value associated with today's manual techniques) to 30 sec.

Approach

Normally, the Denver Center Traffic Management Unit (TMU) is supported by a prototype version of CTAS that operates continuously to provide TMA analysis of traffic conditions. A field-test version of CTAS, developed to support this test, was temporarily installed at Denver and activated only during discrete test periods. DA was operated by a test engineer, and advisories were relayed to the appropriate sector controller. DA trajectory predictions and radar data were recorded for later comparison to determine DA accuracy.

Participation of the commercial flights was coordinated with United Airlines (UAL) on an individual basis over a 3-wk period (September 12–30). The test involved only those flights arriving through the northwest arrival gate (DRAKO). DA clearance procedures and phraseology were developed for the test and were studied from both the pilot's and the controller's perspectives. Many flights included a cockpit observer while all ATC activities were observed at the relevant sectors. Participating controllers and the majority of participating pilots either were debriefed by an observer or completed questionnaires.

The NASA TSRV was operated out of Denver Stapleton International Airport for 1 wk (September 12–18) to complement the commercial-flight test activity. The goal was to conduct the TSRV flights under conditions similar to those for the commercial flights (e.g., route and atmospheric conditions) for later comparisons. Additional flights were conducted into the northeast arrival gate (KEANN) to measure atmospheric characteristics in an area away from the Rocky Mountains, which underlie the DRAKO area. The TSRV provided an opportunity to record aircraft state data and establish more control over test conditions including initial position, altitude, and speed. In addition, the flight-test crew was trained to reduce the influence of variations in pilot technique on DA prediction accuracy.

The test was designed to minimize the impact on ATC and commercial flight operations. Test operations were limited to periods of light arrival traffic in the DRAKO area. These periods typically occurred in the late morning, early afternoon, and evening. This approach provided three advantages: minimum additional workload for controllers and pilots; controlled test conditions that would be comparable over a wide range of flights; and long descent segments which magnify prediction errors. Concurrence of the

flight crew and controllers was required for each participating flight. Both groups were instructed to discontinue test operations at any time if workload became an issue.

Test Setup

The test setup is illustrated in Fig. 1. The CTAS system was located at the CTAS station, an area adjacent to the TMU, approximately 75 ft from the radar-sector positions that participated in the test. The CTAS system was configured on a distributed network of Sun Microsystems Sparc 10 workstations including three 19 in. color monitors and seven processors. CTAS received real-time updates of radar track and flight plan data for arrivals from the Center's Host computer via a one-way (Host-to-CTAS) interface. CTAS also received 3-hr forecast updates of winds and temperatures aloft from the Mesoscale Analysis and Prognostic System (MAPS), predecessor to the Rapid Update Cycle.^{8,9} Normally, the three monitors are used to support a graphical user interface to TMA. For this test, one of the monitors was used to support an experimental graphical user interface to DA. Host track data was displayed to the operator in a planview of the Denver airspace and DA advisory data was superimposed in a tabular list.

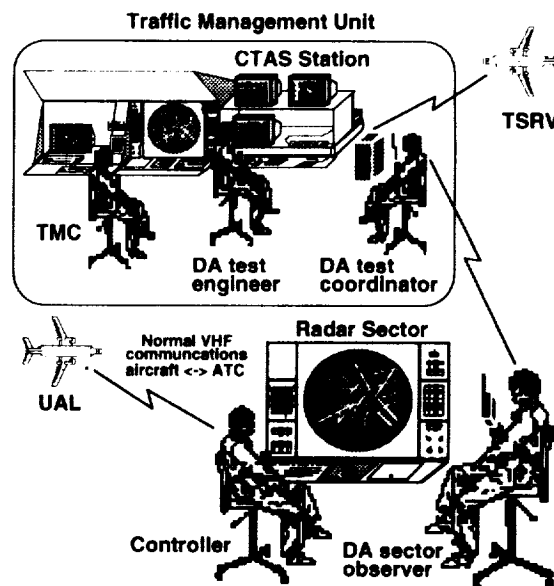


Figure 1. DA test setup.

The CTAS system was operated by a test engineer while a second engineer coordinated test activities between the CTAS station, the sectors, and the NASA TSRV aircraft. DA clearance advisories were relayed to

a sector observer via walkie-talkie, and then were presented to the radar controller on written scripts. The CTAS station included a VHF radio for monitoring communications between ATC and participating aircraft, and for direct communications with the test engineer onboard the NASA TSRV via a dedicated frequency. Indirect communications between the CTAS station and participating UAL flights was supported by the UAL dispatch office. When entering Denver airspace, participating UAL flights were requested to downlink speed, temperature, and wind at cruise via the Aeronautical Communication Addressing and Reporting System (ACARS). These data were relayed to the CTAS station by telephone and used to cross-check the automatic updates of Host track and MAPS atmospheric data.

Figure 2 illustrates the field-test airspace and depicts the general boundaries of the primary test sectors. The primary test sectors, those that issued DA-based clearances, were sectors 13 and 14. Sector 14 is responsible for high-altitude traffic, at or above flight level 240 (FL240), and sector 13 is responsible for low-altitude traffic, below FL240. Typically, sector 14 performs the initial sequencing of high-altitude arrivals, initiates descents to FL240, and then hands off to sector 13. Sector 13 merges the high- and low-altitude arrivals for hand-off to the TRACON at DRAKO. Participating UAL flights typically arrived via one of three routes: J20 from the northwest (Seattle and Portland), J56 from the west (Salt Lake City), or J100 from the southwest (northern California). The NASA TSRV would depart Stapleton at a coordinated time to enter the test area during a traffic lull. The aircraft would then proceed on a round-robin flight plan to perform a series of descent runs along J56 through DRAKO. On some flights, the NASA TSRV would depart the DRAKO area for an atmospheric data collection run through the KEANN arrival gate.

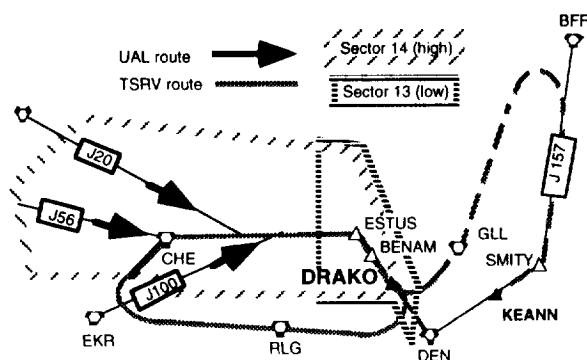


Figure 2. DA field-test airspace.

Test Systems

CTAS System (DA) Functionality

The cornerstone of DA is a trajectory prediction algorithm that models aircraft performance, winds and temperature aloft, and pilot procedures.¹⁰ Trajectory predictions are continually updated to reflect changes in position, altitude, and velocity. Nominally, the predicted path is based on the flight plan route. DA monitors the aircraft to determine if it is tracking the flight plan route. If not, DA generates a path to rejoin the flight plan route or to join another route designated by the controller. Vertical profiles are generated to meet the STA and, at the same time, to be fuel-conservative (i.e., to minimize low-altitude flight) and as close to the operator's preference as possible. DA adapts its trajectory solutions to meet controller-specified constraints in speed, altitude, and path. The intent is to complement individual controller technique and to allow the system to respond to pilot-imposed constraints such as speed changes for turbulence penetration, or heading changes for weather avoidance. DA trajectory solutions are translated into ATC clearance advisories which include TOD and descent speed profile (Mach / Indicated Airspeed (IAS)).[#] In addition, DA monitors each aircraft's progress to provide feedback on the delay (STA-ETA) remaining to be absorbed as well as the aircraft's conformance to the cleared route and vertical profile.

UAL Flights

Participating UAL flights included four aircraft types: Boeing 727 (B727), Boeing 737-200 (B737), Boeing 737-300/500 (B73S), and Boeing 757 (B757). The B727 and B737 are conventionally equipped types that navigate via jet routes defined by VHF Omnidirectional Range (VOR) and Distance Measuring Equipment (DME) navigational aids. The B73S and B757 are FMS-equipped types with both lateral navigation (LNAV) and vertical navigation (VNAV) capability. Many of the B73S aircraft also had required-time-of-arrival (RTA) capability. Although integrated RTA/DA operations have been studied in simulation, the use of RTA was beyond the scope of this test.^{4,11}

[#] Additional DA functionality, not evaluated in this test, includes advisories for cruise speed, cruise altitude, direct-headings, and delay vectors, as well as tools for spacing prediction, conflict probe, conflict resolution, and evaluation of "what if" scenarios.

NASA TSRV

The NASA TSRV is a modified Boeing 737-100 airplane equipped with a research flight deck (RFD) located aft of the conventionally-equipped forward flight deck (FFD).¹² The RFD was equipped with an experimental FMS that was adapted to emulate the LNAV/VNAV functionality found on B73S aircraft. In addition, a modified range/altitude arc was integrated with the LNAV path display to provide the pilot with descent-range guidance along a curved path.

Test Matrix

Participating UAL Revenue Flights

The primary test set for the UAL flights consisted of 24 descents along routes joining J56 and arriving through DRAKO. The 24 descents were divided into 12 cases, each flown twice. The 12 cases represented a combination of three descent speeds (Table 1) and four aircraft types (Table 2). Descent speeds are given in knots IAS (KIAS). The speed set was selected because it would generate a range of simulated delay cases that would be comparable across aircraft types, and because the speeds are ones that most line pilots and controllers would readily accept under a variety of flight conditions. Cruise altitude and cruise speed were not controlled as part of the test. In addition to the primary test set, several cases were run that involved direct routing to BENAM and DRAKO.

Descent Speeds
300 KIAS
280 KIAS
250 KIAS

Table 1. Descent speeds for UAL test set.

Aircraft Type	
FMS equipped	Conventional
B757	B727
B73S	B737

Table 2. Participating UAL aircraft types.

NASA TSRV Flights

The primary test set for the NASA TSRV flights consisted of 24 descent runs, initiated from FL350, along J56 through DRAKO. The 24 runs were divided into 12 cases, each flown twice. The 12 cases

represented a combination of three speed profiles (Table 3) and four levels of vertical profile guidance (Table 4). The speed profile cases were selected to span the aircraft's speed envelope and to include significant deceleration segments at the top and bottom of descent. The four cases of vertical profile guidance were defined in terms of cockpit automation and TOD definition. For the first case, the flight crew initiated descent at the DA TOD and applied conventional techniques to monitor and correct the vertical profile. For the second case, the flight crew initiated descent at the VNAV TOD and followed the VNAV path. The third case called for the flight crew to initiate descent at the DA TOD and then join the VNAV path in descent. The fourth case also initiated descent at the DA TOD, but employed the modified range/altitude arc for vertical path guidance.

Speed Profiles	
(Cruise)	(Descent)
0.76 Mach	320 KIAS
0.72 Mach	280 KIAS
0.76 Mach	240 KIAS

Table 3. Speed profiles for TSRV test set.

Vertical Profile Guidance	
Cockpit Automation	TOD Definition
Conventional (FFD)	DA
FMS VNAV (RFD)	FMS VNAV
FMS VNAV (RFD)	DA
Range/Altitude (RFD)	DA

Table 4. Guidance cases for TSRV test set.

DA Procedures, Phraseology, and Training

An integrated team developed the DA clearance procedures, phraseology, and associated training for participating flight crews and controllers. The team included pilot and controller experts, FAA air traffic procedures specialists, and human factors and CTAS engineers. The procedures and phraseology were developed from previous evaluations and were refined for use during the field test.¹³

DA Procedures

Figures 3 and 4 illustrate the basic DA descent procedure in terms of an aircraft's horizontal and vertical profiles, respectively, for a DRAKO arrival. The horizontal profile begins at the aircraft's initial

position and follows the aircraft's assigned route of flight to the meter fix (DRAKO in Figure 3). The horizontal profile is marked to indicate the along-path distance to the meter fix for comparisons with the vertical profile. The vertical profile begins at the initial altitude and follows the DA descent procedure along the path to the meter-fix crossing.

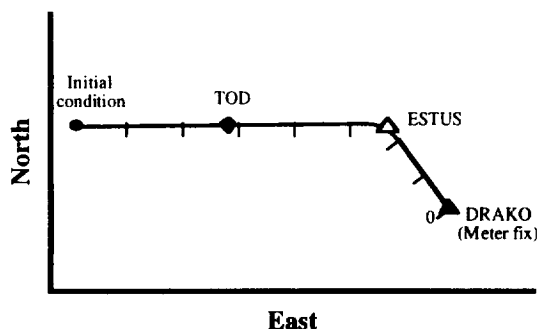


Figure 3. Horizontal profile.

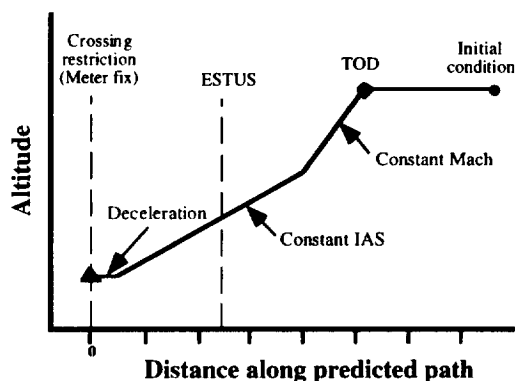


Figure 4. Vertical profile.

The DA descent procedure is defined by at least three vertical profile constraints: a TOD; a Mach/IAS descent speed profile; and a descent crossing restriction at a fix (typically altitude and speed).** Procedurally, the TOD is the point where the aircraft is to initiate the altitude change or initiate deceleration to the assigned descent speed. The procedure calls for the pilot to maintain an assigned descent speed profile until deceleration is necessary to meet a speed restriction. Both the TOD and the descent speed profile are DA generated advisories. The crossing restriction is

** The descent crossing restriction was defined at the meter fix for this test, but in general may be defined anywhere along the horizontal path. Additional vertical profile constraints may be defined by the controller or published procedure.

generally specified as part of a published airspace procedure.

Positive control over TOD and crossing restrictions is important to ATC. The TOD is critical for monitoring altitude conformance and for predicting and controlling separation. Crossing restrictions provide procedural separation between traffic streams and across airspace boundaries, and improve predictability.

Participating UAL flights were instructed to cross DRAKO at FL200 at 250 knots. This crossing altitude was negotiated with UAL to allow a consistent crossing altitude over the range of test conditions whereas the nominal ATC procedure would have allowed an altitude window at DRAKO. All flights were issued a descent airspeed and instructed to maintain their cruise Mach if a descent Mach segment was appropriate. For conventional aircraft types, the pilot was instructed to begin the descent procedure at the DA TOD. The DA TOD was normally issued by ATC 20–40 n.mi. prior to descent and was specified in terms of a DME range from a VOR defining the current leg of the aircraft's route.

For FMS-equipped aircraft, UAL negotiated a slightly different procedure based on a strong desire to maximize the usage of their FMS equipment. The procedure called for the pilot to build and fly a VNAV path based on the crossing restriction and DA descent speed. It was expected that the differences between the VNAV and DA TODs would be small (on the order of 1–5 n.mi.) because the DA algorithms were so similar to those used for the FMS trajectory calculations. The primary differences between DA and FMS trajectory predictions are due to differences in input data such as models of atmospheric characteristics and aircraft performance. Whereas many FMS systems may have more accurate performance data, DA automatically incorporates updates of atmospheric data over the entire trajectory.

The NASA TSRV used similar procedures with two exceptions. In all cases, DA descents were made to the lowest possible crossing altitude at the meter fix (17,000 ft mean sea level). The objective was to generate the longest possible descents to challenge DA prediction accuracy. The second exception was related to the inclusion of two procedures within the TSRV test set that called for the pilot to initiate the descent at the CTAS/ DA TOD and then transition to the VNAV path, or to the modified range/altitude arc, for vertical profile guidance.

Phraseology

The test procedures called for three separate ATC transmissions to complete the DA procedure. The first transmission was required by the FAA to confirm that the flight crew was willing to participate in the test. This transmission was also used to confirm the crossing restriction associated with the test procedure. The transmission was usually made when an arrival was 150–200 n.mi. from Denver. For example,

"UAL123,
expect CTAS Descent Procedure,
plan to cross DRAKO at FL200 at 250 knots."

The second transmission was a clearance containing the DA descent speed for all aircraft, as well as the DA TOD if the aircraft was a conventional type. This clearance was issued by the sector-14 controller when the flight was 20–40 n.mi. from the DA TOD. Stratification of the arrival sectors required the issuance of a descent limit at FL240. For example,

Conventionally equipped aircraft:

"UAL123,
descend and maintain FL240;
for CTAS Descent Procedure,
begin descent 70 miles from the Meeker VORTAC;
descend at 280 knots; if unable, advise."

FMS-equipped aircraft:

"UAL123,
descend at pilot's discretion, maintain FL240;
for CTAS Descent Procedure, descend at 280 knots;
if unable, advise."

After handoff to the sector-13 (low-altitude) controller, the third clearance was issued to continue the descent to the DRAKO crossing restriction. For example,

"UAL123,
cross DRAKO at and maintain FL200 at 250 knots;
Denver altimeter is ___, maintain CTAS Descent Procedure."

Training

Logistical limitations severely limited the training options for participating UAL flight crews and controllers. Sector staffing practices and the randomness of traffic conditions excluded the option of identifying participating controllers and flight crews in advance. Instead, pilots and controllers were invited to participate in the test if they were on duty during a test

period. All sector-13/14 controllers received a 1-hr briefing, and were encouraged to consult with test engineers if questions arose during the test. The approach for training UAL flight crews was to issue a briefing package to each potential crew, along with their flight planning papers, just prior to departure. Distribution of the briefing package was facilitated by UAL flight operations offices throughout northern California and the Pacific Northwest. With the exception of a few coincidental repeats, the UAL pilots flew the DA descent procedure with no prior practice. In contrast, the NASA TSRV crew received ground instruction and several hours of flight and simulation practice.

Scenario

During the evening before each test day, a test plan was created to identify potential test periods and UAL flights. The plan was based on predicted weather, expected traffic conditions, and the test cases which remained to be completed. The plan was used to schedule cockpit observers, brief Center staff, distribute briefing packages to UAL flight crews, and plan NASA TSRV flight operations. Just before each test period, a TMC monitored the actual traffic conditions to update the test plan. NASA TSRV departures were coordinated to conduct as many descent runs as possible during periods of light traffic. With the concurrence of the TMU, the CTAS system was switched to the test version about 45 min before the first aircraft crossed DRAKO. The supervisor and controllers for sectors 13 and 14 were briefed on the desired speed conditions for each participating aircraft and were consulted for modifications. UAL dispatch was contacted by phone to obtain cruise state data from participating flights via ACARS. In a few instances, the MAPS wind profile was uplinked to the crews of FMS-equipped types.

Once an aircraft entered Sector-14 airspace, the CTAS engineer relayed an approximate DA TOD to the sector. This information was provided to the controller who surveyed the traffic situation to assess workload for an un-interrupted descent. If the desired speed condition was unacceptable, the controller was given the options of either choosing an alternative descent speed and/or routing, or excluding the flight from the test. If the situation was acceptable, the controller made the first transmission to confirm pilot participation. When a participating aircraft was within 30–40 n.mi. of the DA TOD, the CTAS engineer relayed the advisory to the controllers and recorded the DA trajectory prediction. If the situation was still acceptable to the controller, the DA clearance was issued to the aircraft.

After the handoff from sector 14, the sector-13 controller would assess the situation and issue the final clearance to remove the FL240 restriction.

Preliminary Results and Discussion

A total of 97 UAL flights participated in the field test by executing the DA descent procedure. Preliminary results are presented that are based on the analysis of the primary test set of 24 descents completed during the last week of testing. Figures 5–8 illustrate the accuracy of DA horizontal and vertical profile predictions for typical cases involving a conventional and an FMS-equipped aircraft. The cases occurred within 2 hr of each other under relatively stable atmospheric conditions. Both aircraft arrived via the J100..J56 route and were issued DA clearances based on a 300-knot descent speed. The conventional case involved a B727 cruising at FL370, at Mach 0.82; the FMS case involved a B757 cruising at FL410, at Mach 0.80.

Figures 5 and 6 show comparisons of the actual radar track and the DA-predicted ground track for the conventional and FMS example cases, respectively. The plots are based on the Denver Center radar tracking coordinate system (origin located approximately 600

n.mi. southwest of Denver). For the conventional case, the aircraft deviates left of J100 (up to 2 n.mi.) as it tracks outbound on the Meeker (EKR) 060° radial. The cross-track error is reduced as the flight joins J56 to track the Hayden (CHE) 076° radial, but is then increased as the aircraft overshoots the turn at ESTUS. The navigational errors, which added approximately 1.5 n.mi. to the aircraft's actual path flown, contributed the equivalent of 12 sec (late) to the aircraft's total time error. In comparison, the FMS aircraft flew the route with an order-of-magnitude less cross-track error and no discernible overshoot in the turns.

Figures 7 and 8 compare the mode-C altitude reports to the DA-predicted vertical profiles. The conventional aircraft initiated descent about 1 n.mi. after the DA TOD, whereas the FMS aircraft (using its VNAV TOD) initiated descent about 3.5 n.mi. before the DA TOD. The conventional aircraft paralleled the DA vertical profile well during the constant-Mach segment of the descent and then crossed below the DA vertical profile as it descended below FL280. The most significant altitude error, which developed in the latter half of descent, correlates directly with the overshoot at ESTUS. As the aircraft approached DRAKO, the pilot detected the slightly low altitude for the crossing restriction and reduced the descent angle slightly. The flight arrived at DRAKO 18 sec late while meeting the

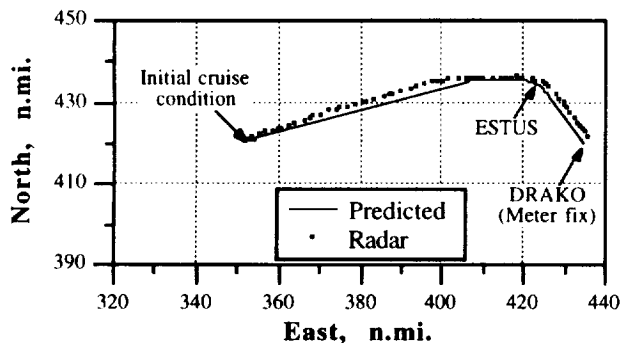


Figure 5. Ground track for conventional aircraft case.

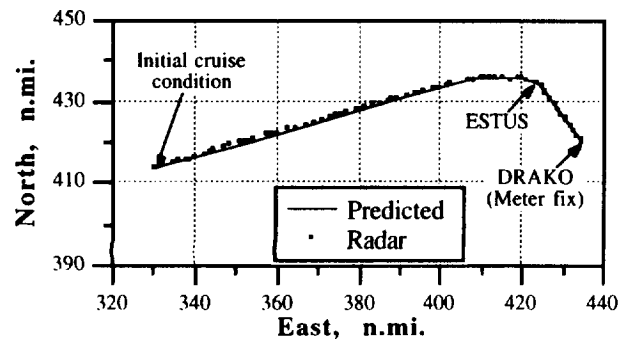


Figure 6. Ground track for FMS aircraft case.

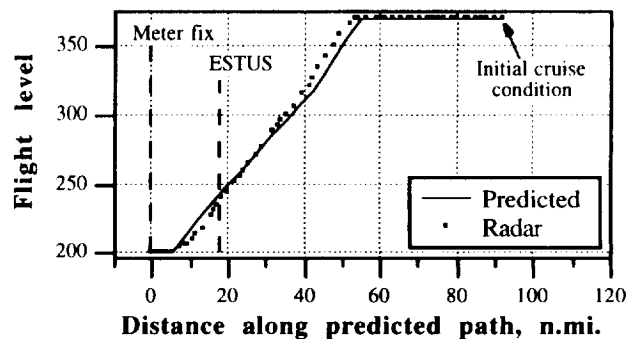


Figure 7. Vertical profile for conventional aircraft case.

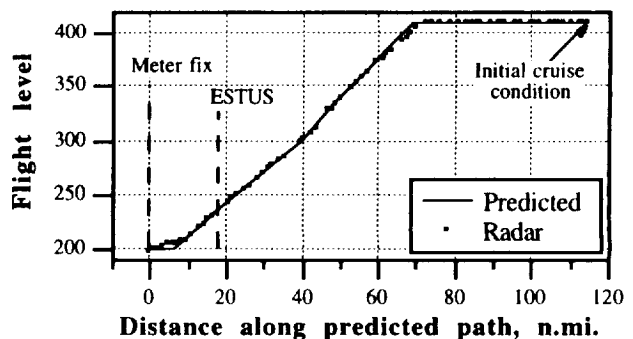


Figure 8. Vertical profile for FMS aircraft case.

crossing restrictions. In comparison, the FMS aircraft's VNAV descent closely matched the DA prediction resulting in a DRAKO arrival of 6 seconds late.

Table 5 presents a summary of the arrival time errors for the primary test set of 24 UAL commercial flights. These results, based on the use of a single advisory prior to TOD, are consistent with previous simulation and flight test results. In addition, the effect of aircraft automation was clearly evident. FMS capability had a direct impact on time error by improving horizontal navigation accuracy. In addition, the FMS capability of closed-loop VNAV guidance greatly increased the accuracy of DA altitude predictions in the latter half of the descent. The NASA TSRV flights, in general, yielded similar results.¹² Although the total sample of test cases was not large enough for the results to be statistically significant, the data indicate that the 20 second DA accuracy goal is achievable under field conditions. Considering that DA will provide the controller with continuous advisory updates, even during descent, it is reasonable to expect even greater accuracy with the issuance of mid-descent corrections. Since airspace stratification already results in the updating of an aircraft's descent clearance (after a handoff from a high-altitude sector), DA advisory updates could be appended, if necessary, with a minimum increase in controller workload.

Aircraft Type (Equipment)	Arrival Time Error
All	2.4 ± 13.1
Conventional	7.4 ± 14.3
FMS	-2.5 ± 10.0

Table 5. Arrival time errors (radar crossing time - DA ETA), mean ± S.D.

Insights from the pilot's perspective were gained from cockpit observations of 39 of the participating flights and questionnaires returned from 64 pilots.¹³ The written briefing package was sufficient for training, and overall pilot reactions to the procedure were positive. Although slightly more than half of the responding pilots indicated that they had to adjust thrust or drag to maintain the vertical profile, fewer than 10% indicated that they "needed to make unusual corrections to meet the constraints at the bottom of descent." Comparisons of pilot responses yield an interesting complement to the trajectory data. Fifty-seven percent of the pilots flying conventional types, based on the DA TOD, had to make corrections (usually increased thrust). These comments were consistent with the added

path distance most pilots flew as a result of navigational errors. Although a significantly smaller percentage of pilots were expected to make corrections when flying FMS types, based on their VNAV TOD, 51% of these pilots also had to make corrections (usually increases in drag).

Additional insights from the ATC perspective were gained from sector observations and controller interviews. Thirty controllers participated in the test and were generally debriefed immediately after a test session. Evaluation of controller acceptance was limited in this test because of the absence of a controller interface to DA; only issues relative to the procedures and DA accuracy were relevant. Debriefings and observations indicated that the majority of controllers were skeptical of DA at first. However, acceptance improved as controllers gained more experience from issuing the advisories, monitoring the effects, and, in some cases, competing directly with the DA predictions. All the DA TOD advisories were acceptable from the controller standpoint and several controllers commented that the TODs were consistently later (i.e., closer to the meter fix) than the TODs they would normally have issued.

Comparisons of pilot and controller responses revealed an interesting paradox with regard to the issuance of a TOD with crossing restrictions. For conventional aircraft types, the DA TOD was an effective means for increasing the predictability of the vertical profile. Although this was beneficial to the controllers, the pilots indicated that they were sometimes uncomfortable during descent in determining whether they would meet the crossing restrictions. In many instances, pilots considered themselves high on path during the descent when, in fact, they had to eventually add power near the bottom. This subject deserves further study. Regarding FMS-equipped aircraft, pilots generally considered the DA procedure to be routine whereas controllers indicated that they were not comfortable in allowing aircraft to descend at the VNAV TOD (effectively a pilot's discretion descent) under all traffic conditions. Even with accurate DA predictions of TOD, positive control is required to ensure separation under certain conditions. Modifications to the DA procedure for FMS-equipped aircraft are necessary to address the controller's concerns while still taking advantage of the FMS capability.

Concluding Remarks

The September 1994 DA field test generated a valuable set of data for evaluating DA trajectory prediction accuracy, identifying significant sources of error, and gaining insight into the procedural and training issues that are associated with DA operations. This was the first time a DA advisory was issued to a commercial flight as a descent clearance. Results indicate that DA, with one advisory prior to TOD, can achieve an arrival time accuracy of less than 20 sec error. The use of FMS greatly increased the precision of clearance conformance with a corresponding improvement in DA trajectory prediction accuracy.

Participating pilots and controllers were supportive of the test. Pilots were able to execute all of the defined DA procedures, and the written briefings were sufficient for training. Two issues were uncovered in relation to the DA descent procedures: for conventional aircraft types, fuel-conservative DA descent profiles may be difficult for pilots to monitor in some situations; for FMS-equipped aircraft, controllers expressed concern that VNAV-initiated descents are not feasible under higher traffic loads. These procedures must be refined because controller and pilot "comfort level" are as critical to CTAS success as trajectory prediction accuracy.

Additional analysis of the data from this field test will include evaluation of altitude and position errors along the predicted path, analysis of cases outside of the primary UAL test set, and comparison of the UAL and NASA TSRV data sets. The field-test data will be fed into a comprehensive FAA-sponsored sensitivity study that has been initiated to analyze the sensitivity of CTAS trajectory and conflict predictions to realistic errors (including errors in the modeling of aircraft performance and atmospheric conditions, pilot conformance, and radar tracking). Current plans call for a series of DA simulations and field tests, beginning in fall 1995, to evaluate DA algorithms and controller interface issues under progressively more challenging traffic conditions.

Acknowledgments

The authors would like to acknowledge the contributions of the CTAS development team, most notably Francis Richason, Michelle Eshow, and Debbie Chao. In addition, the field test would not have been possible without the enthusiastic support of Jim King

and the CTAS site support staff, Randy Kelley of United Airlines, and all the Area 1 controllers and TMU personnel at Denver Center.

References

- ¹Erzberger, H., Davis, T.J., and Green, S.M.: "Design of Center-TRACON Automation System." Proceedings of the AGARD Guidance and Control Panel 56th Symposium on Machine Intelligence in Air Traffic Management, Berlin, Germany, 1993, pp. 11-1-11-12.
- ²den Braven, W.: "Design and Evaluation of an Advanced Air-Ground Data-Link System for Air Traffic Control." NASA TM-103899, January, 1992.
- ³Williams, D.H., and Green, S.M.: "Piloted Simulation of an Air-Ground Profile Negotiation Process in a Time-Based Air Traffic Control Environment." NASA TM-107748, April, 1993.
- ⁴Green, S.M., Williams, D.H., and den Braven, W.: "Development and Evaluation of a Profile Negotiation Process for Integrating Aircraft and Air Traffic Control Automation." NASA TM-4360, April, 1993.
- ⁵Slattery, R., and Green, S.M.: "Conflict-Free Trajectory Planning for Air Traffic Control Automation." NASA TM-108790, January, 1994.
- ⁶Green, S.M., H., Davis, T.J., and Erzberger, H.: "A Piloted Simulator Evaluation of a Ground-Based 4D Descent Advisor Algorithm." Proceedings of the 1987 AIAA Conference on Guidance, Navigation, and Control, Monterey, CA, August, 1987, pp. 1171-1180.
- ⁷Davis, T.J., and Green, S.M.: "Piloted Simulation of a Ground-Based Time-Control Concept for Air Traffic Control." NASA TM-101085, June, 1989.
- ⁸Benjamin, S. G., Bleck, R., Grell, G., Pan, Z., Smith, T. L., Brown, J., Ramer, J., Miller, P., and Brundage, K.: "Aviation Forecasts from the Hybrid-b Version of MAPS -Effects of a New Vertical Coordinate and Improved Model Physics." Preprints, Fifth Conference on Aviation Weather Systems, Vienna, VA. American Meteorological Society, J5-J9, 1993.
- ⁹Benjamin, S. G., Brundage, K. J., Miller, P. A., Smith, T. L., Grell, A., Kim, D., Brown, J. M., Schlatter, T. W., and Morone, L. L. : "The Rapid

Update Cycle at NMC." Preprints, Tenth Conference on Numerical Weather Prediction, Portland, OR, American Meteorological Society, 1994.

¹⁰Slattery, R., Zhao, Y. : "En-Route Descent Trajectory Synthesis for Air Traffic Control Automation." American Control Conference, Seattle, WA, June 21-23, 1995.

¹¹Williams, D.H., and Green, S.M. : "Airborne Four-Dimensional Flight Management in a Time-Based Air Traffic Control Environment." NASA TM-4249, 1991.

¹²Oseguera, R.M., and Williams, D.H. : "Flight Evaluation of the CTAS Descent Advisor Trajectory Prediction." American Control Conference, Seattle, WA, June 21-23, 1995.

¹³Palmer, E., Goka, T., Cashion, P., Feary, M., Smith, N., and Graham, H.: "Development and Initial Field Evaluation of Flight Deck Procedures for Flying CTAS Descent Clearances" Proceedings of the Eighth International Symposium on Aviation Psychology, Columbus, Ohio, 1995.